Modelling Considerations for Dynamic Soil-Structure Interaction of Offshore Wind Turbine Foundations

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MODELLING CONSIDERATIONS FOR DYNAMIC SOIL–STRUCTURE INTERACTION OF OFFSHORE WIND TURBINE FOUNDATIONS

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INTRODUCTION

Wind, waves, ice and earthquakes cause time-varying loads on offshore wind turbines (OWTs). Proper design of OWTs and their foundations requires insight into the excitation and the dynamic properties of the system. In this context, measurements show that calculations typically provide biased resonance frequencies. Thus, prototype OWTs show a stiffer response than predicted in the design phase. In addition to this, the properties of soil are highly uncertain, and the seabed may change properties over time due to cyclic action, scour and backfilling. Poor estimation of the fatigue life of an OWT may result from inappropriate modelling of the stiffness and damping associated with the soil and foundation. Hence, assessment of these properties has recently been in focus. The next sections briefly summarize some of the findings by the offshore-foundations research group at Aalborg University, Aalborg, Denmark.

DYNAMIC STIFFNESS AND DAMPING OF WIND TURBINE FOUNDATIONS

Soil and foundations can be modelled by numerical methods such as the finite-element method (FEM) or the boundary-element method (BEM). Semi-empirical or semi-analytical methods provide an alternative and usually more efficient approach. In any case, a model must provide realistic estimates of for the soil response. The soil stiffness decreases with increasing shear strain magnitudes, and the transition from drained behaviour into undrained behaviour causes an increase of the stiffness. In the frequency range covering this transition, damping occurs as result of pore water seepage. This damping adds to the friction between grains that increases with increasing cyclic deformation levels. Furthermore, geometrical dissipation (or radiation damping) sets in with increasing frequency. Especially, in layered soil the foundation must be excited above the cut-on frequency for wave propagation in the layer to obtain any significant radiation damping. Evidently, only advanced models can account for all effects. Hence, analyses are usually performed using simplified and linearized approaches.

Regarding uncertainties related to the soil, Andersen et al. (2012) performed a probabilistic analysis of the fundamental frequency of an OWT based on a monopile, modelling the undrained shear strength as a stochastic process over depth and applying a Winkler model for the pile–soil interaction. The fundamental frequency of the OWT was found to have a coefficient of variation (COV) of about 2–3% due to variations of the soil properties deemed realistic for a real seabed. Vahdatirad et al. (2014) performed a similar analysis of an OWT on a gravity-base footing, finding a similar COV for the fundamental frequency.

Damgaard et al. (2014) compared measured frequencies of OWT tower vibration during emergency shut down to the frequencies predicted by design models. Four offshore wind farms were analysed, finding that the frequencies varied over time. Scour and backfilling around the monopiles were found to be the most likely cause of this variation. Furthermore, a part of the bias could be explained by partially undrained behaviour of the soil. Design methods typically assume drained behaviour of the soil, but even sand provides a nearly undrained response at the low frequencies (0.2–0.3 Hz) associated with the fundamental frequency of a large OWT. As a consequence of this, Bayat, Andersen and Ibsen (2016) proposed the use of p-y-ẏ curves and a Kelvin model accounting for frequency-dependent stiffness as well as the seepage-related damping instead of the classical p-y curves and a Winkler model only representing soil stiffness.

LUMPED-PARAMETER MODELS FOR WIND-TURBINE FOUNDATIONS

Aero-hydro-servo-elastic codes are applied in the design phase for evaluation of loads on OWTs. Such codes represent the rotor, nacelle, tower and support structure by few degrees of freedom (d.o.f.), and only few more d.o.f. can be added to account for dynamic soil–structure interaction (SSI). One approach is to use "macro models" fitted to the response of, for example, rigorous FEM models. However, for fast evaluation of dynamic SSI, an efficient alternative may be the use of consistent lumped-parameter models (LPMs) as suggested, for example, by Damgaard, Andersen and Ibsen (2014) who analysed the response of a 5 MW OWT on a gravity-base foundation. With reference to Figure 1, the main principle of an LPM is to fit a set of simple mechanical systems (springs, dashpots and masses) to match, in an approximate manner, the frequency response of the foundation. LPMs can be formulated for any type of foundation, and due to the high computational efficiency, LPMs combined with aero-hydro-servo-elastic codes can be used for probabilistic analysis of wind turbines. For example, Damgaard et al. (2015) performed probabilistic analysis of fatigue of a monopile.

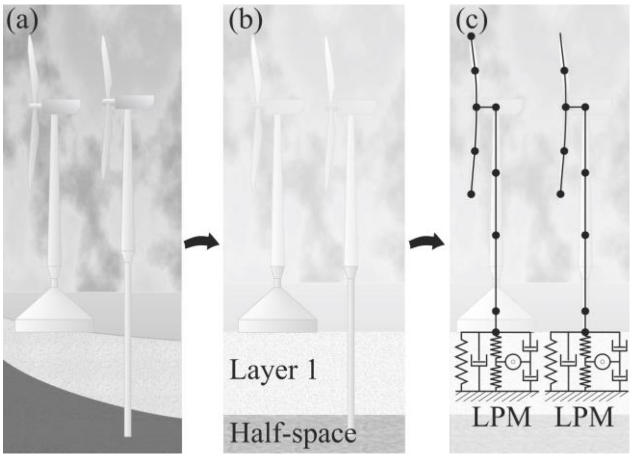

Figure 1: Steps in formulation of lumped-parameter model: a) real system; b) rigorous frequency-domain model of soil and foundation; c) consistent LPM.

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